Mars Surface Exploration Technology Options

C. R. Weisbin, G. Rodriguez

Jet l'repulsion Laboratory, California Institute of Technology

Pasadena, (California 91109

1. Introduction

Exploration **of** Mars **is a** major thrust of **NASA, Some of** the important goals of this exploration are (1) the search for life and understanding of evolution of the planet, (2.) the discovery of accessible. wale.r, (3) understanding how the climate has changed, and (4) developing an inventory of useful resources, as a precursor 10 human exploration. The purpose is to understand broadly the evolution, geology, geochemistry, organic chemistry, and climate and 10 this knowledge widely available to the public.

While many useful scientific investigations can be done in situ on the surface of Mars, there seems to be agreement that the main scientific objectives of' exploration can only be achieved with the return of samples 10 Earth for analysis. I lowever, a sample return mission from Mars is a very significant undertaking. Al tho ugh vigorous attempts arc now being made to develop new programmatic approaches to lower the cost of such a mission, a Mars Sample Return (MSR) mission is unlikely to be affordable with current technological appr oaches. In the meanwhile, NASA plans a series of' nea rer-t erm exploration missions which will provide important in situ data on Martian materials, but not as mu I as a sample return. These planned nearer-term affordable missions will be vital in solidifying, capabilities for a series of" evolving Mars missions with ever increasing capabilities. To this end, the NASA Mars Surveyor program is planning a ser ies of surface exploration missions to be launched in 1998, 2001, and 2.()()3, as precursors 10 a possible sample return mission in as early as 2005".

This paper provides an overview 01' a set of technological options being enabled for Mars exploration, under a technology development program sponsorsed by the NASA Office of Space Across and Technology. T 'his technolog y development program, designated as the Mars Exploration Technology (MET) program, supports the following task elements:

- **Precision Landing -** to enable site selection and safe landing in more. interesting landing areas.
- **Sampling System** - for acquisition and handling of soil, rock and subsurface. samples. A prototype of this system was demonstrated in May 1995, and used as a foundation for a successful proposal for integration of a similar system with an approve.(i science payload in the Mars 98 mission.
- **in-silu Propellant Production - aimed** at terrestrial prototype evaluation of leading system concepts for use of the Martian atmosphere to produce fuel and ox ygen as propel lants for the return trip 10 Earth.
- **in-Silu Instruments -** focusing on a miniature, Nuclear Magnetic Resonance Spectrometer for detecting and characterizing water in various di fferent states.
- **Low Temperature High Density Electronics-** conducting studies 10 identify materials and designs for high density electronics packaging for multi-chip modules that will survive in the Mars thermal environment.

- **Thermal Control"** - developing a warm electronics enclosure for critical electronic components and instruments, using phase materials, diode heat pipes, and aerogel insulation for d i urnal temperature control.

- **High-Performance, Low Temperature Batteries** - which fabricates and evaluates the performance of experimental cel Is and batteries capable of ultimately operating properly at -60 degrees C.

- **Miniature Transponder** - developing a new miniature (< **2.5** kg) transponder including: a narrow bandwidth Phase Lock Loop (<20Hz) with a carrier tracking threshold of -158 dBm; a wide dynamic range (>70 dB)'; and **a** command detector functionality for multi-user compatibility.

Highly relevant to Mars exploration are the technologi es of miniaturized microrovers capable of survival and mobility on the Martian surface. In addition to the technolog ies listed above, this paper also discusses the main goal s and achievements of the rover technology activities under this program:

- **Miniture Planetary Rovers** - developing technologies' in miniaturization, long range mobility, and mobile science acquisition.

The rest of the paper describes the goals and main :lclllc\'L'l)lc.ills to date m each of these area as.

1. Precision Landing

Precision landing is an important and enabling capability for several future Mars missions, because many interesting areas of scientific investigation on Mars are either small in extent or are in regions of hazardous terrain. Precision landing may also be crucial to Mars sample ret urn scenarios in which a sample is left from a previous mission to be acquired by a return vehicle via a rover or arms. Also, Mars landing site selection is based primarily on science objectives and landing safely. Sele ction of safe and scientifically inte resting landing loca tions is complicated by large dispersions or uncertainties in the actual landed position relative to the desired locat ion,

Based on today's technology, these landing location errors can be more than **150** km. Most of this error derives from two sources: navigation errors in the approach to Mars, and corrup tion 01 the trajectory during the entry phase by aerodynamic uncertainties. II is also in these two mission phases, the planetary appr oach phase and the e ntry phase, where the control power exists to correct errors on this magnitude. in the subsequent mission phases, the parachute phase. and the terminal descent phase, landing location correction is limited to a few km at best, and may result in undesirable increases to the landed mass.

A strategy has been developed for improving the accuracy and precision of landings on Mars:

The. Approach/Entry Phase. and the Terminal Descent Phase can be considered as separate and distinct portions of the landing mission, with an interface at parachute deployment. The ability to conduct precision landings in the Terminal Phase. is independent of what happens in the previous phases, while landing acc uracy is dependent, at least down to the kilometer level, only on control (luring the Approach and Entry Phases.

For the Approach/Entry Phase, the goal is to reduce the position error at parachute deployment below the current value of about l150l km. Reduction to l50l km would be of use, but reduction to less than l10l km is needed before accurate, prec ision landings scan be accomplished.

For the Terminal Descent Phase, the goal is to navigate up to 10 km to compensate for 1) errors in parachute deployment left over from the approach/entry phase; 2) wind -induced errors while on the parachute; and 3) map-tie errors. It is assumed that a propulsion system and radar altimeter are required, regardless o f precision landing requirements, just to provide a soft landing with no horizontal motion. Both accuracy and precision in this phase require the ability to sense target-relative location and/or to sense. hazards.

The use of optical approach navigation using the Martian moons, Phobos and Deimos, has been e valuated. This study used realistic assumptions on the camera system performance (a ~lcl]lc.lllillc-like narrow angle camera), satellite ephemeris knowledge accuracy, an(l center-finding capability for the non-spherical moons of Mars. The results show signific ant improvement over radio-only navigation in the Approach Phase. The study to-date indicates the. viability of this optical technique for improving Approach Navigation Phase accuracy. Several technical issues remain to be solved before the use of (m-board optical navigation in the Approach Phase of a Mars landing mission can be demonstrated. Algorithms to be used for on-board image processing and orbit determination must be developed and simulated in the presence of realistic error sources. Requiremen ts 011 spacecraft systems m ust be developed and evaluated to provide attitude control for camera pointing and stability. The impact of this optical navigation technique on mission design and sequencing will be significant, requiring maneuvering in attitude and velocity changes late in the Approach Phase.

Aerodynamic control during the entry phase would enable the capability for low and medium lift entry bodies to provide the control authority needed to correct for expected errors in entry conditions and for atmosphere density uncertainties. Results so far indicate that a medium lift entry body ($L/D = 1.1$) can provide the needed authority to correct the worst expected errors. The question of whether a low lift entry body ($L/D = 0.3$) can correct for atmospheric density uncertainties, in the presence of reduced errors in entry conditions, is being investigated.

Terminal Descent

A review of methods for acquiring and using imaging data during the terminal descent phase is identifying the most promising techniques for development. Data types being considered for use in this phase include images taken in visible and/or infrared light (passive or active), radar and/or lidar images or altimetric data, and active or passive beacons implaced by previous landers or impacters.There is a significant body of previous work in this area. In general, this work was not carried to a conclusion or to flight, and the question of what systems, or even what frequencies should or could be used to acquire navigation data in this phase is still open.

1. In Situ Propellant Production

Use of the Martian atmosphere to produce oxygen, and possibly hydrocarbon propellant for a return trip to Earth can dramatically lower the mission payload and hence the cost and launch requirements of a Mars Sample Return mission. A figure of merit for this technology is the mass that must be landed to return a sample of any given weight and diversity of Mars materials to Earth. The degree to which ISPP reduces this mass is the main value of ISPP. This value must be compared against the additional complexity and risk associated with use of ISPP, as well as the cost of developing and implementing ISPP. Various elements of prototype hardware to demonstrate these processes have been developed by several organizations, notably Martin Marietta and the University of Arizona. The object now is to take these beginnings, and demonstrate that viable systems can be produced from them. Ultimately, these chemical conversion systems must be integrated and combined with storage/cryogenic systems, energy systems, and propulsion systems.

A typical Mars ISPP process includes many steps ranging from carrying propellant tanks to Mars surface, to compressing the Martian atmosphere, chemically converting CO_2 to O_2 and possibly a hydrocarbon propellant, compressing, cooling and liquefying product gases and storing in empty propellant tanks and lifting off using thrusters specifically designed for the propellants produced.<p>

Basically, there are two overall processes which are the front-runners for ISPP, and these have some potential variants.

One process uses the Sabatier/Electrolysis (S/E) process, in which hydrogen (brought from Earth) is reacted with compressed CO_2 in a heated chemical reactor:

[1] $CO_2 + 4\,H_2 \;\text{----->}\; CH_4 + 2\,H_2O$<p>
The methane so formed is collected and saved for use as a propellant. The water is collected, deionized, and electrolyzed in an electrolysis cell:

$$2H_2O + \text{electricity} \;\text{------>}\; 2H_2 + O_2$$

The oxygen is saved for use as a propellant. The S/E process has been studied in some detail ("Mars Sample Return with In Situ Resource Utilization," Final report, Contract NAS 9-19145, Martin-Marietta Corp., Jan. 13, 1995) at a lab bench level. The great advantage of this process is that it is fairly well understood and seems to work well as a system. There do not seem to be any fundamental technological challenges ahead in further perfection of the conversion plant system, although a number of engineering improvements are necessary. There are two potential problems with the S/E process. One is that the process is fairly complex and requires a number of vessels and considerable plumbing, which could drive the mass up and increase system risk. The other, which appears to be more serious, is the requirement of bringing hydrogen from Earth. This is a potential mass/cost driver for a mission, and at this juncture, it is not even clear that there is a technology whereby hydrogen can be brought from Earth and stored on Mars. If the S/E process is to be developed to a flight system, it will be important to investigate hydrogen storage.

The second process, typically known as the "zirconia approach," partially dissociates Martian CO_2 and utilizes a solid state electrolyte (typically yttria-stabilized zirconia at ~ 900°C) to transport oxygen ions across a membrane in order to remove O_2 from the partially dissociated mixture. This requires a suitable catalyst/electrode at the surface of the electrolyte to convert gaseous oxygen to oxygen ions.

The great attraction of the zirconia process is the conceptual Simplicity of the oxygen separation process and the potential for a compact cell. However, in practice, the tradition has been to rely on tubular ceramic cells for test purposes. These are not compact, and appear to be structurally flimsy and liable to failure under launch or landing loads. A new concept for combining planar fuel cell geometry with the use of rugged single crystal sheets of zirconia holds promise for simple, inexpensive, rugged zirconia assemblies. However, these must be proven by experiment.

The overall comparison of mass and power requirements of the zirconia and Sabatier/electrolysis processes depends on a number of factors which remain uncertain at this point. One of the reasons to conduct development work on both processes is to clarify the parameters of this comparison.

Other ISPP approaches have been proposed. These are under review. They include use of the Reverse Water Gas Shift reaction to enhance oxygen production, possible use of a gas discharge front-end for Zirconia, and possible use of diborane and carbon dioxide as propellants.

In developing ISPP, our goal is to demonstrate a viable technology in the form of a compact, flight-like unit which can be tested in a relevant environment, at as early a date as possible. Due to limits on the funding available and the state of the technology, it was decided that a viable program plan must be limited by the following constraints: (1) We will concentrate on the two most advanced technologies: Sabatier/Electrolysis and Zirconia; (2) Initial work will be concentrated on determining the performance characteristics and general viability of the S/E and Zirconia processes in laboratory bench scale prototypes.

When sufficient data become available to assure that at least one of these processes is indeed viable, the more attractive of these will be selected for demonstration as a compact, flight-like unit which can be tested in a relevant environment. Technology development on the interface technologies which tie directly to ISPP: (i) thermal and power management, (ii) compatibility with designs and configurations of descent and ascent vehicles, and (iii) gas pressurization, liquefaction and cryogenic storage, and (iv) compatibility with propulsion systems (gas-fed, and thruster performance) will follow closely after demonstration of compact, flight-like unit. We will stay alert to new ideas in ISPP as they arise, and consider funding their exploration, but only as a second priority behind developing S/E or Zirconia to the demonstration stage.

The plan for ISPP development calls for further development of the two competing processes (S/E and Zirconia) over a 17 month period, having starting in April 1995, with a comprehensive review and decision point in August, 1996 as to which approach to select for further development.

1. Sample Acquisition

Even for a low cost sample return, careful sample selection will be necessary, and rocks are highly desirable, although constraints may be such that only loose soil and pebbles may be collected. In Ref. 1, size and power limitations were thought to preclude sawing or coring, and it was hoped that the need for unweathered rock would be answered by collecting pebbles and utilizing material from their interiors. However, the ability to chip or core during the sample collection process itself might still prove feasible, and could be of great scientific value. Furthermore, a mission concerned with water detection would probably concentrate on acquisition of sub-soil samples by drilling.

It is possible that in order to reduce costs, future MSR planners may accept smaller samples, but there appears to be a consensus of opinion of the minimum desired sample size. Ref. 13 assumes a 5 kg sample on the grounds that "the MESUR-based sample return study, conducted by Lockheed-Martin and JPL in 1993, determined that for any given sample, 100 grams of material is sufficient to correctly characterize the sample type." However, 5 kg is recommended as "a reasonable starting point" for the total sample set in order to carry out needed analyses on a range of samples.

Sampling requirements for Mars surface exploration missions are also under development. Thirty-six of the 64 potential Mars surface instruments would require horizontal deployment on the surface, with roughly 2/3 of these requiring deployment distances of $\leq$ 1 m, and about 1/3 requiring deployment distances of 1 to 10 m. Two instruments need deployment distances greater than 10 m (Ref. 15). Some instruments require vertical deployment with a mast or balloon. Thirty-nine instruments require bringing a sample back to the instrument. Of these, 17 required soil, 11 rock, 7 unweathered rock, 2 duricrust and 2 required ice. Surface manipulators to acquire these sample were suggested as scoops, soil cores, trenchers, chippers, augers and drills.

Specifically, this program will develop capabilities in the following sampling technology areas:

- visual user interfaces and work silt calibration for the opc.rater's sample selection

- efficient control of robotic motions dill-i]lg sampling (ftcc.-spacc, guarded, and contact) including powcr an(1 energy conservation/management

- sensor processing/perception for robot guidance, sample acquisition and analysis

- robot control behavior for robust autonomy in response to real-1 ime sensor data

- control architecture integrating sensor and knowledge-driven sampling activities

The focus of the task is on mid-term Mars Surveyor science goals- the Mars 2001 Lander is representative, with evolution to Mars Sample Return a longer range task technology objective. R&D partnerships with the science community, NASA and outside, foster coherent sampling concepts, flight robotics technology insertion, and coupling to NASA strategic goals of cost-effective sl))all-scale technologies.

Specifically, Inc. task has made significant technological contributions to enhance the Mars '98 Lander science capabi lities. An accelerated effort was made in FY95 to define a relevant robotic sample acquisition subsystem for 1998 flight science integration. Progress in this work was demonstrated in laboratory technology concept demonstrations occuring in May 1995, and teaming relationships with science investigators succesfully proposing to the Mars '98 Science package.

1. in Situ Instruments

The search for water (when, where, form and amount) acts is a common thread for many of the scientific objectives in Mars surface exploration. In situ instruments have been identified as an important need. With this great emphasis (m water, it was decided to develop an instrument uniquely capable of detecting and characterizing water in different states, a miniature Magnetic Resonance Spectrometer (}{cl'. 21). Resonance instruments work on the principle that a magnetic field is applied to the sample, thus splitting the energy levels of either the nuclear or electronic spin states , and then energy is pumped into the states. Measurement is made of either the energy absorbed, or the re-emitted energy as a function of wavelength. Characteristic spectra reveal the composition of the sample. The advantages of magnetic resonance techniques are that: samples are tested under ambient conditions; minimal preparation or disruption of samples (gram to milligram); analysis is not confounded by sample matrix; the spectrum is molecule-specific.

The special features of Nuclear Magnetic resonance (NMR) are that it can detect the presence of: water in soil, minerals, rocks; free waler in pore.s; adsorbed wale.r on surfaces; chemically bound wale.r. The special features Of EPR are that it can detect: nature of oxidant in Martian soil; oxidation stale of paramagnetic ions in soil (mineralogy); characterization of volatiles (carbonates, sulfates; radicals in icy samples (characterization al impurity level); organics in subsoil.

Laboratory instruments use cw (change of impedance) or pulsed mode (observe re-emitted radial. These instrum ents use. large electromagnets to apply the magnetic field. For a space instrument, a miniature permanent magnet system would be used (Ref. 24). The scanning method would depend on tile application. Scanning at fixed magnetic field with variable frequency is relatively easy for NMR because circuitry to scan rf radiation is readily available. On the other hand, EPR requires scanning at microwave frequencies and this poses much more of a chal lenge.

A goal of this task is to exploit prototype instrument probe systems for preliminary in-situ characterization of Martian surface. chemistry, and to support the sample selection, and site selection objectives. The goal is to utilize innovative new technology in an external detection mode, which (km not require a separate sampling procedure for analysis. Since the search for wale.r has been chosen as a central theme for Mars exploration, initial emphasis in our program is (m building and testing of a miniature Magnetic Resonance Spectrometer (MRS) with combine.(i capabilities of Nuclear Magnetic Resonance (NMR) and Elec tron Paramagn etic Resonance **(Iii'1<).** Conventional NMR and EPR systems in the laboratory employ very large, heavy electromagnets and sweep the magnetic field to obse rve spectra. Miniaturization is achieved by using small permanent magnets, and a tunable RF cavity to achie ve a frequency sweep. It is projected that mass reduction of several hundred to one will be possible.. This would provide a n(m-invasive analytical technique with a unique combination of capabilities such as detection of water, characterization of volatiles, active oxygen species, oxidation stales of paramagnetic ions, and detection of possible organics from soil, minerals and rocks.

Recent i y achieved results included demonstration of a High Sensitivity R F Magnetic field Antenna Sensor Demonstration. A miniature. RF antenna was demonstrated (scan range of 1 MHz - 2 MHz) that fits into a miniature NMR spectrometer probe in CW and pulsed modes. This antenna was combined with NMR signal processing circuit using a laboratory electromagnet. Tests were conducted of spectrometer sensitivity with standard proton NMR samples and geologic samples (clay). This required development of a near-field (1-3 cm) wideband RF antenna technology with specified radiation field configuration as well as signal detection with high sensivitity.

1. Planetary Microrovers

The science rover task develops technologies that enable 20 Kg class microrovers to autonomously traverse many kilometers on the surface of Mars and perform scientist directed experiments and return relevant data back to Earth. Present microrover technology, as represented by the Sojourner rover in the Mars Pathfinder mission, has several limitations that preclude more ambitious science rich missions. Current microrovers have very limited traverse (10s of meters), are not capable of sample acquisition and manipulation (i.e., soil and rock acquisition, subsurface access, emplacement of instruments), have limited science packages onboard, are designed for short term missions (10 days), and require careful and repetitive ground monitoring and control (limited autonomy)

There is great interest in the science community to explore Mars by landing near interesting geographic areas and moving to pre-selected targets to offset landing errors. It is desirable to place instruments against outcrops or loose rocks, possibly collect rocks for return to Earth, and search an area for sample of interest. Also, long traverse will provide an opportunity to make observations and measurements along traverses and to access a wide variety of rocks from different regions of Mars.

Efforts at JPL, in collaboration with leading universities and industry, have focused on development and terrestrial demonstration of three types of microrover vehicles:

- 12--15 kg rovers capable of carrying a science payload of about 5-6 kg. These rovers will have the capability to perform on the surface of Mars important new tasks in macro and micro imaging, visual and near-infrared spectroscopy, sample acquisition and manipulation.

- 5- kg miniaturized rovers capable of higher-yield, longer duration science -- for both equatorial and polar Martian extremes. Fundamental issues include reducing mass and volume of rover structural and actuator design, achieving high density power; delivery over wide thermal ranges, maintaining a stable thermal environment; creating new classes of ultra-light, environmentally resistant miniaturized robotic sampling devices; controlling force contact tasks of an ultra-light rover-manipulator platform on uneven terrain; and integrating broad-capability science instruments into these rover architectural innovations.

- Extremely small automated or remotely-controlled vehicles which open new application frontiers by breakthroughs in mass reduction. One of these possible applications is the use of nanorovers (robotic vehicles of the order of 10-50 grams) in planetary exploration. Such vehicles could be used, for example, to survey areas around a lander, or even to be distributed along the lander descent trajectory, and to look for a particular substance such as water ice or microfossils.

1. Low Temperature, High Density Electronics

The objective of this work is to assure that the new breakthroughs in high density electronic packaging now becoming available, which were designed for warm applications, can survive the Martian night in a state-of-the-art thermal enclosure. The approach to survivable electronics will be to develop models for the physical processes that cause failure under thermal cycling, and to verify these through test. This will allow us to assess the survivability of present designs under various thermal stresses, as well as to propose alternative designs for high density flight electronics that avoid these failure modes.

This task will produce specific designs, including materials, for high density electronics that will survive on Mars or in other extreme temperature

temperature environments. An integral part of this effort is pioneering work in the characterization and modeling of failure mechanisms of high density electronics hardware.

Miniaturized flight electronics are needed which can operate on the surface of Mars. Multi-Chip Modules (MCM's) are under development for warm electrThe objective of this work is to assure that the new breakthroughs in high onics which will offer significant reductions in size and weight. There are two questions: (1) Will these electronic packages survive and function (m the surface of Mars?; ('2) if not, how can their design be modified to make them survivable?

Conventional approaches to evaluating and controlling failure risk of electronic components are not effective for critical failure modes of Multi-Chip Modules (MCM's). It is not possible, by testing alone, to verify acceptable low failure risk for critical damage-accumulation failure. modes that are indigenous to MCM 's. However, failure risk due to damage-accumulation fai lure modes can be effectively evaluated and controlled using a Probabilistic Physics of Failure (P2oF) approach that incor porates both testing and analytical model ing based on fundamental analyses of the physics and mechanics of fail ure mechanisms.

In P2oF, probabilistic models bawd on the physics of failure phenomena provide a framework for incorporating information from mater ials and component testing, inspection (NDE/NDI), and environmental characterization, even when such information is va.gut, approximate, sparse, or uncertain.

MCM-D multi -chip module packaging technology wi i i be eval uated to determine probabil i tics of fai lu c when subjected to thermal cycling characteristic of the Mars surface, and specific failure modes and associated design aspects wiii be identified. The probabilities of failure will bc (ick'mine. d as a function of the thermal variations to which the electronics arc subjected.

In the unlikely event that it will be found that the electronics (designed for warm cllVirollllc.ills) will function adequately in the Mats environment, nothing further I) eed be done.]11 the more likely event that the probability of failure is 100" high 10 be acre. pl:lblc., we will do two things:

(i) Specify the maximum allowable range of thermal variation (as achieved by advanced thermal control) to meet adequate standards of reliablity.

(ii) Specify specific design changes in the multi-chip module packaging technology which wiii eliminate or significantly reduce the probability of major failure modes, thus significantly improving reliability in a Mars-like enviornment.

The main achievements to date include: 1) identify three to ten critical low-temperature failure modes for high density electronic packaging substrate technology (MCM-D), beginning with the n-Chip substrate; 2) establish a working relationship (data exchange, MCM-D substrates for cbarficlcriz.slim, etc .) with MCM-D manufacturers; 3) Charac terize residual stress and relevant physical features of the multilayer, thin film structure of the n-Chip substrates; **4)** Develop a probabilistic li fc prediction model based on the physics of the low-temperature, damage-accum ulation failure processes that includes the characterization of residual stress and physical features of the n-Chip substrate; **5)** Apply the. probabilistic pilysics-of-failure (P2oF) model to assess life of the n-Chip module for a range of the.rn)al cycles including that of the Mars environment, considering the major life and risk drivers which include the depth of thermal cycles, physical features and (lime.nsi(ms of substrate layers, lilt. size range.s of possible manufacturing defects, and the materials used for substrate layers.

1. Thermal Control

The Martian environment provides a very wide variation in ambient temperature from day to night. Most electronics developed for us (m Earth require operating temperat ures in the range 233 Kelvin to 313 Kelvin, and limits for survival in extreme temperatures. **W** hiie it is hoped that some. day, special electronics will be developed which can survive low temperatures and possibly even operate at low temperatures, the continuing pressure to drive costs down (m space missions usually implies that low -cost standard electronics developed for mom temperature operat ion wil I bc employed on f uture Mars Landers. Protecting electronics, batteries and other components from the low temperat ure night environment is a critical need of Mars Lander missions.

} 'uture Mars Landers are expected to (i raw thei r power from photovoltaic cells. **As a** result, significant power will only be available during sunlit hours. While batteries can bc used to provide minimal power over night, the power they can supply is limited, and furthermore, they must be protected from very low temperatures at night. 11 is exactly when temperatures are lowest that the least power is availa ble for heaters to maintain the warmth of key components.

In order to cope with this problem, tile Mars Pathfinder anti 98 Lander missions will house electronics and batteries within enclosures which arc very effectively insulated, and which contain Radioisotope Heating Units (RHUS) whit.il produce a considerable amount of heat for their mass (- 1 W per 50 g). Because mass is always very scarce, lightweight enclosures have been developed using ultra-efficient insulation (Ref. 27). However RHUs are no longer being produced. 11 is expected that RHUs will probably not be available for Mars missions after the 1998 launch.

Without RHUs to provide heal overnight, such warm electronics enclosures will go through very wide temperature swings during the diurnal cycle, despite the excellent warm electronics box (WEB) design developed by Hickey et. al. Therefore, post- 1998 Mars Landers face a potential crisis in thermal control. Based on recent modelling, it is believed that the. best way to provide thermal control in the absence of RHUs is to collect and store heat during the (lay when the sun shines, and release the heat at night to significantly reduce the diurnal temperature variation in an electronics/battery enclosure. There is a ready seam of heat during the day because the photovoltaic sways associated with the lander operate above room temperature, and the frames or supports for these PV arrays may be regarded as an essentially infinite heal source. for needs during the day.

Heat can be stored efficiently in phase-change material (PCM) which is a material that undergoes repeated cycles of melting and resolidification when heated and cooled at periodic intervals. Dodecane, with its melting point of about 260K, is an obvious choice, for our application. Heat can be transported from the PV arrays to the PCM within the enclosure by means of a miniature heat pipe filled with a substance such as propylene.

A viable design concept for a warm electronics enclosure has been dci'eloped, fabricated and fully tested for atmospheric and 10 torr ambient pressures, and simulated Mars thermal environment. The enclosure consisted of a 6-inch cubical box that included 5 Dodecane PCM panels and one Dodecane PCM pane] swith integrated butane diode. heat pipe fabricated under a JPL contract to Energy Sciences Laboratory. These panels, assembled to form a cubical enclosure, were enclosed within a foam insulated box. The tests evaluated the perforamnce of the enclosure through 3 diurnal thermal cycles, with heating applied to a simulated electronics mass to simulate a typical electronics payload duty cycle. The tests showed reproducible phase transitions and maintained interior test temperatures within the range -?5 to +20 degrees Celsius.

1. High Performance, Low Temperature Batteries

Batteries arc the ideal choice as primary power sources and for augmenting other power systems during peak loads in NASA's space missions. Various battery systems, including primary $Li/SOCl_2$ or rechargeable Ni/Cd or Ni/H, are currently used depending on the energy requirements and longevity of the mission. Most of these battery systems have attractive specific energy and power densities; however, the desired performance is limited to a narrow temperature range of -20 to +70 °C. Also, the realizable efficiencies and energy densities of these systems are rather low at sub-zero temperatures. The ambient temperature of some of the planetary missions arc math lower than -20 °C. This necessitates insulation of the battery from extreme ambient temperatures prevalent al planetary surfaces and possibly a warm up of the battery by another energy source. No known electrochemical system functions efficiently in such extremely cold environments. Here, we propose. to carry out studies leading to an identification and evaluation of such a cryogenic battery system, based (m our present understanding of the advanced lithium battery systems. Rechargeable lithium batteries have a higher specific energy (2-3 lime.s) and a higher energy density (2-3 times) compared to state-of-the-art batteries such as Ni-Cd and $Ni-H_2$. In addition, these batteries have longer storage life and a lower self discharge rate. In view of these advantages, rechargeable lithium batteries arc. presently being considered for several commercial/terrestrial applic.slims where weight, volume., and cycle life are critical. The advantages of reduced mass and volume also make these batteries attractive for aerospace applications.

The overall objective of this program is to develop a low temperature battery with high specific. energy and energy density and to demonstrate the technology for the. Mars Exploration program. The nominal program plan is from FY 951099. The specific objective of the FY 95 effort is to develop electrode and electrolyte materials for low temperature batteries.

A series of tests have been conducted to find suitable electrolyte solutions based on the solve.nts that remain in the liquid phase. at low temperature. The feasibility of the low temperature cell concept has been demonstrated. The test cells arc. stored in an environmental chamber capable of controlling the ceil temperature. The electrical performance and cycle life performance characteristics of these cells at low temperature is then evaluated. Successful experiments were conducted to cycle. EC-based electrolyte experimental test cells at -20 C. Investigations continue on novel electrolyte systems that can operate at -40 to -60 C.

1. small Deep Space Transponder

The object is 10 develop a miniature X-band deep spat. c transponder. This involves two major technology developments, one being a digital X-band receiver using advanced GaAs Monolithic Microwave Integrated Circuit (MMIC) technology, and the other involves development of miniature high-frequency high-density electronic packaging technology. The combination of these two technology advances will enable a new miniature transponder with unsurpassed performance:

- Narrow bandwidth Phase 1 .ock Loop (<20Hz) with a carrier tracking threshold of -158 dBm.
- Wide dynamic range (>70 dB)
- Command Detector functionality (for multi-user compatibility)
- Total mass <2.5 kg.

In the past, deep space telecommunication systems for space.craf(have been developed individually 10 fit the requirements of each spacecraft project. Since past spacecraft tended to be heavy, expensive, and power hungry, telecommunication systems based on past spacecraft designs arc. inappropriate for use on new miniaturized spacecraft. For Mats Landers launched from Med-Lite launch vehicles, mass, power and volume arc precious commodit s, and it is crucial that a truly miniaturized, high efficiency telecommunication system be developed for this kind of application. Acknowledgements.

1. Concluding Remarks

Technologies are under development which are targetted [0 important needs of Mars surface exploration missions. Early versions of this technology is ready for near-lcin] mission opportunities. Successful infusion of the sampling system technology into the planned Mars 98 mission is an example of an early application. Other technologies, such as in-situ resource utilization, respond to longer term missions.

1. Acknowledgements

'1 'he rest'at ch described in [his paper was performed al the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space. Administration.

This paper focuses primarily on an o\Jcr\'it\\' of the Mats Exploration Technology (MET) program, which reports to NASA through the Office of the Technology and Applications Directorate 01'.11'1., in support of the JPL Mars Exploration Program. Efforts in planetary rovers and sampling are supported by tasks in NASA's Telerobotics program. The JPL Mars Exploration Program generates technology requirements and relative priorities for technological focus.

The contributions to this paper from the leaders for the individual tasks, and their colleagues, within the.sc. programs were essential, and are gratefully acknowledged: S. Kim, R. Manvi, N. Moore., G. Powell, S. Rae, and P. Schenker. Valuable contributions from the Mars Exploration Program Office at JPL were also pivotal in determining the program contents and balance; acknowledgments here arc due to: S. Bailey, L. Lowry, P. Satin, J. B. Mc Namee, and D. Shirley.

1. References

1. "Concepts for a Small Sample. Return Mission Using Microtechnology," JPL Internal Document D-8822, October, 1991.

2. "Mars Sample Return 1984 Study Report," JPL Internal Document D-1845> Sept. 28, 19'$4.

3. "Low Cost Mars Sample Return Study," Briefing for NASA HQ Code SL, R. A. Wallace, JPL, 15 November, 1994. "Low Cost Mars Sample Return Study," Briefing for NASA HQ Code S1., R. A. Wallace, JPL, 13 February 1995. "Mars Sample Return" Final Report, Lockheed-Martin Corp. Report No. MCR 95-1301, Contract JPL-959902.

4. "Autonomous Hazard Detection and Avoidance for Mars Exploration," H. Pien, AIAA Computing in Aerospace -8 Baltimore, MD, 21-'24 October 1991.

5, "Achieving Safe Autonomous Landings on Mars Using Vision-Based Approaches," 11. Pien, SPIE Advances in Intelligent Robotic Systems Conf. Cooperative Intelligent Robotics in Space II, Boston, MA, 11-15 November 1991.

6. "Sensor Trade Study, Vol 11: Autonomous Precision Landing," M. Trichel, et al., Final Report prepared for JSC, Erim, July 1990.

7. "Planetary Terminal Descent Simulation with Autonomous Hazard Avoidance., " J. Cuseo, C. Dallas, 27th AIAA Aerospace Sciences Mtg, Reno, NV, 9-12 Jan, 1989.

8. "Planetary Lander Vehicles Utilizing LEAP Technology," 30th AIAA/ASME/SAE/ASEE Jt.

PropulsionConf., Indianapolis, IN, 27-29 June, 1994.

9. "Feasibility of Rocket Propellant Production on Mars," R. 1.. Ash, W. Dowler, and G. Varsi, Acta Astronautica 5,705-724 (1 978)

1 (). "Mass and Power Estimates for Martian In-Situ Propellant Production Systems," R. Frisbee, JPL Internal Document D-3648 (1986).

1 1 . "Recent Concepts in Missions to Ma rs: Extraterrestrial Processes," K. Ramohalli, E. Lawton and R. Ash, Jour. of Propulsion and Power 5, 181-187 (1989).

12. "Martian Rc.source. Utilization 1. Plant Design and Transportation Selection Criteria," P. Kaloupis, P. Nolan and A. Cutler, Space Power 11, 343-375 (1992).

13. "The Mars ISRU Sample R c turn Mission Study Report," M. ('c.rime.lc and J. Connolly, JSC Report, MISR Project, D. Kaplan, Manager, draft, October 1, 1994.

14. "Mat-s Sample Return Mission Utilizing In-Situ Propellant Production," R. Zubrin and S, Price, Final Report of Study Conducted for JSC by Lockheed-Martin Corp., March 31, 1995.

15. "Mars Surveyor Science Objectives and Measurements Requirements Workshop," Edited by D. J. McCleese, S. Squyres, S. Smrekar, and J. Plescia, JPL Internal Document D12017, 199-1,

16. "Distribution of Rock Sizes at the Viking Sites for Purposes o f Estimating Probability of a Hazardous Landing," preliminary manuscript, M. Golombek and D. Rapp, J]'].,May 5, 1995.

17. "Beyond-the-Horizon Mars Technology Study," JPL Internal Document D12084, September 2 9 , 1994.

18. "Advanced Concepts, M iniconference on Thermal Control," JPL Miniconference Proceedings, January 24, 1995.

19. "Satellite Thermal Control 1 landbook ," The Aerospace Corporation Press, 1994.

?.(). "Characterization of Martian Surface Chemistry by a Miniature Magnetic Resonance Spectrometer," in "Mars Surveyor Science Objectives and Measurements Requirements Workshop," S. S. Kim and J. G. Bradley, Jet Propulsion laboratory, Pasadena, CA, May 10-12, 1994, pp.93-94.

21. "Novel NMR Apparatus for Investigating an External Sample," R.L. Kleinberg, A. Sezginer, D. D. Griffin and M. Fukuhara, J. Mag. Res., 97, 466-485 (1992)

22. "Remote (Inside-[)ul) NMR.]11. Detection of Nuclear Magnetic Resonance in a Remotely Produced Region of Homogeneous Magnetic Field," J. A. Jackson, L. J. Burnt.u and F. Harmon, J. Mag. Res., 41 ,411-421 (1980)

2 3 . "Portable ESR Spectrometer with NEOMAX (Nd-Fe-B) Permanent Magnet Circuit," A. Nakanishi, N. Sugahara and A, Furuse, Int. J. Rad. Appl. and Instrum., Part A, Appl. Rad. & Isotopes, 44, 357-360 (1 993)

24. "Sampling of Planetary Su rface Solids for Unmanned In Situ Geological and Biological Analysis: Strategy, Principles and Instrument Requirmeents," D. B. Nash, NASA Technical Report 32-1225, November, 1967.

25. "MESUR Lander Arm Study," Presentation to JPL, S. Price, Martin-Marietta Corp., Dec. 18, 1992.

?(). "Current Slate of Robotic End Effector Technolo gy with respect to Planetary Surface Sample Acquisition Issues," JPL IOM (internal document), C. Moreno to B. Muirhead, February 8, 1989.

27. "Integrated Lightweight Structure and Thermal Insulation for Mars Row," G. S. Hickey, D. Braun, L. Wen and H. Eisen, JPL Division 35, to be submitted to ICES, 1995,